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On the nature of quasi periodic oscillations in the black hole candidate GRS1915+105

Sivakumar G. Manickam and Sandip K. Chakrabarti
S. N. Bose National Centre For Basic Sciences
JD Block, Sector-III, Salt Lake. Calcutta-700091, India
email: sivman@boson.bose.res.in & chakraba@boson.bose.res.in

Abstract. We analyze RXTE data of the transient black hole candidate GRS1915+105 and find that the Quasi Periodic Oscillations (QPO) are of variable frequency. Power density spectra reveal that there is more power in high energy X-rays, indicating that the QPO might be originated due to shock oscillations. A few timescales have been identified and generally it is found that the longest time-scale ($\sim 100s$) is related to the time it takes to fill the volume upto sonic sphere, and the shorter time scale ($\sim 0.1s$) is related to the free-fall time in the post-shock region.

Keywords : Black holes, neutron stars, X-ray sources, outflows

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1. Introduction

GRS1915+105 is a well known black hole candidate in our galaxy which exhibits very rich time-variability in a large number of time scales. Morgan et al. [1] pointed out that the source is sometimes in low-hard state, but in other times it goes to flare state with considerable variations in amplitude and frequency. In the flare state, the photon flux is seen to vary by a factor of ten or more. Paul et al. [2] showed that in the flare state itself, when the flux decreases from burst to quiescence, very little time is taken, indicating quick disappearance of matter into the black hole in infall time scale. Morgan et al. [1] pointed out that there are several time-scales of quasi periodic oscillations (QPO) ranging from 67Hz to 0.01 Hz (See also, Muno et al. [3]). Yadav et al. [4] made a startling discovery. X-ray spectra seem to reveal a transition from hard to soft state when changing from quiescence to burst phase of the flare state. Since this transition takes place in a matter of few seconds, they ruled out the possibility that actual viscous time scale may be in operation. Rather, they claim that the sub-Keplerian component is playing a major role in the hard-soft transition as predicted by Chakrabarti and Titarchuk [5] and Chakrabarti [6]. Recently, Rao et al. [7] went a step further and showed that even the spectrum in the burst and quiescence states show the characteristic slopes of soft and hard states respetively, establishing that sub-Keplerian flows play major role in state transition exactly as predicted [5].

In the present paper, we study the nature of QPO in GRS1915+105 in much more detail in that, we analyze individual bursts and quiescence and show how the power density spectrum and the spectrum itself evolve. We conclusively prove that shock oscillation causes the QPOs of 2-10Hz by showing that the QPO disappears in the 0-4keV pre-shock Keplerian flow, and is present only in high energy part of the spectra. The QPO frequency itself is found to be highly variable from one quiescence to another. The transition from burst to quiescence is explained by recent outflow model of Chakrabarti [8-9]. This model also explains the variation of QPO frequencies. Details of our results are presented elsewhere [10].

2. Observational results

We analyze public domain data of RXTE taken on the followings dates:

1. Case A: October 7th, 1996
2. Case B: May 26th, 1997
3. Case C: June 18th, 1997

First, we discuss these three cases separately and finally we discuss the general implications.

2.1. *Results of Case A*

Figure 1 shows the light curve on the right vertical panel and the power-spectrum of a few segments of data on the left vertical panel. Light curve shows that the source oscillates between 'Off' state and 'On' state. In the off-states, photon flux is very small, around 2000 photons/s/keV while the on-states produce ten to twenty times larger photons. The off-states are generally 'well behaved' and less chaotic, while the on-states are extremely noisy, and variable. Specially, second half of the on-states show oscillations. Off states repeat every thousands of seconds. The mean time of the occurrences of off-states are marked on the right panel by a number which corresponds to time (in seconds) that has passed since that particular observation began.

Power spectra calculated at each off-state are shown on the left panel where normalized power is drawn along the y-axis (in arbitrary units) and frequency (in Hz) is drawn along the x-axis. The prominent peaks representing QPOs are joined by a dashed curve to indicate variations in the QPO frequency as the system evolves. The duration of the off-states generally decreases with time on

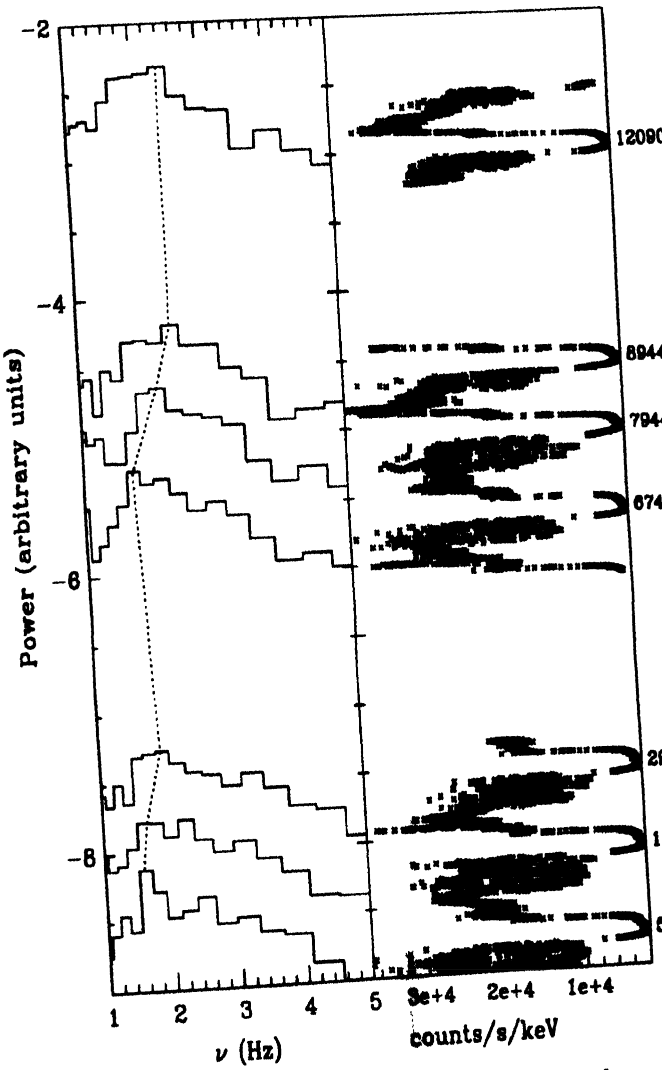

Figure 1. Plot of the light curve (right panel) and evolution of power density spectrum (left panel) of Case A data of Oct. 7th, 1996. Off-states analyzed are marked by the time of observations on the right axis. The QPO frequencies are connected by a dashed curve to highlight the evolution of ν_{QPO} with time.

this day and the QPO frequency generally increases as well. The explanations are given in the next section.

Figures 2(a-b) show the details of the light curve and the power spectra of the off- and on-states which took place between $\sim$ 400s and $\sim$ 1600s. In Fig. 2a, three regions, namely 'Off', 'On_{+}' and 'On_{++}' states are marked. In

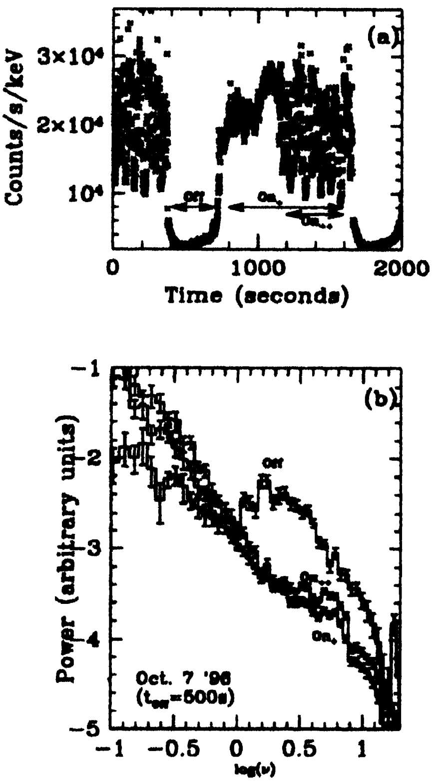

Figure 2(a-b) First off-state of Case A data (a) and power spectrum of the Ofl and On_+ and On_{++} states (b). Off, On_+, On_{++} states are marked.

the later part of the so-called on-state there are oscillations in the count rate, but the oscillation is not big enough to go to the 'Off' state. In Fig. 2b, power spectra for there three segments are shown. In the 'Off' state, a distinct QPO at around 1.6 Hz is present. This is absent in the On_+ and On_{++} states but a new QPO at around 5Hz is present here, especially so in the On_{++} state. Closer examination reveals that there is a very weak and narrow feature at this frequency even in the Off state.

A further analysis of power density spectrum computed using data in separate energy bands indicate that the QPO is present only in the hard X-rays (5-13keV) and is absent in the soft X-rays (0-4keV). This will be discussed in detail using Case C data below.

Spectral analysis of this data reveals that the system actually oscillated between the hard and soft spectral states while going from 'Off' and 'On' states. This agrees with observations of Yadav et al. [4] and Rao et al. [7] for the data labeled as Case C.

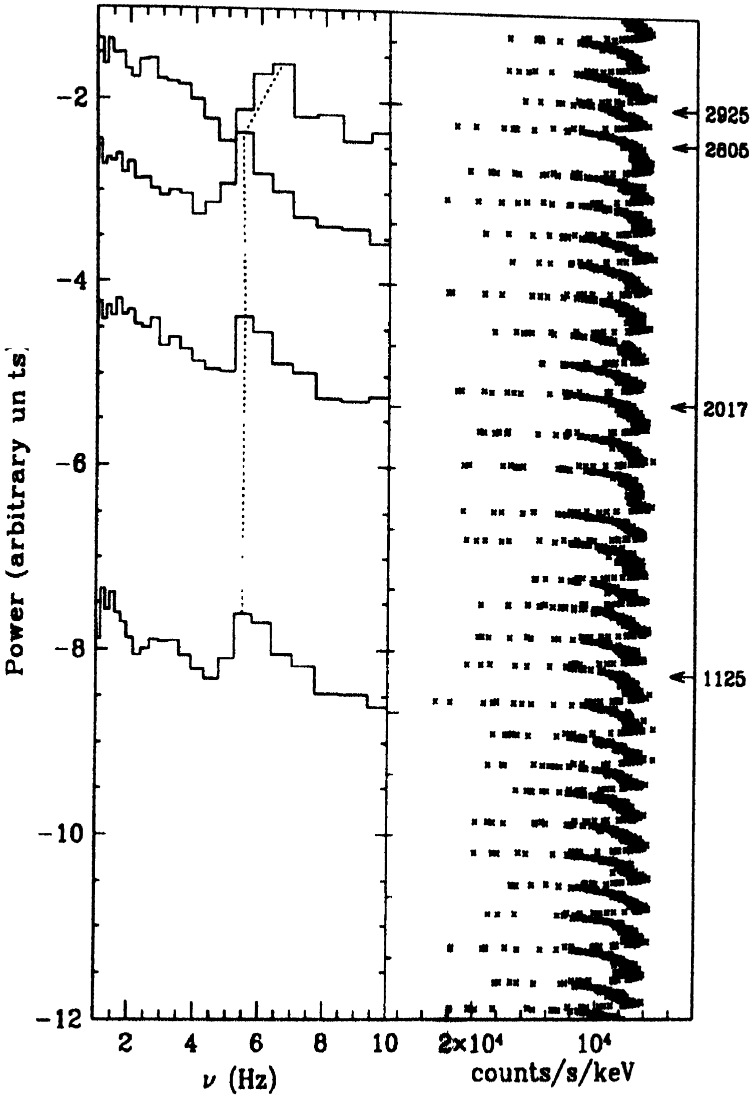

Figure 3. Plot of the light curve (right panel) and evolution of power density spectrum (left panel) of Case B data of May 26th, 1997. Off-states analyzed are marked by the time of observations on the right axis. The QPO frequencies are connected by a dashed curve to highlight the evolution of ν_{QPO} with time.

2.2. *Results of Case B*

Figure 3 is drawn exactly in the same way as the Figure 1 with data from Case B. Unlike Case A, this case is highly regular, but the on-states are present only momentarily. Duration of off-states shows small variation. Small variation is seen in the QPO frequency as well.

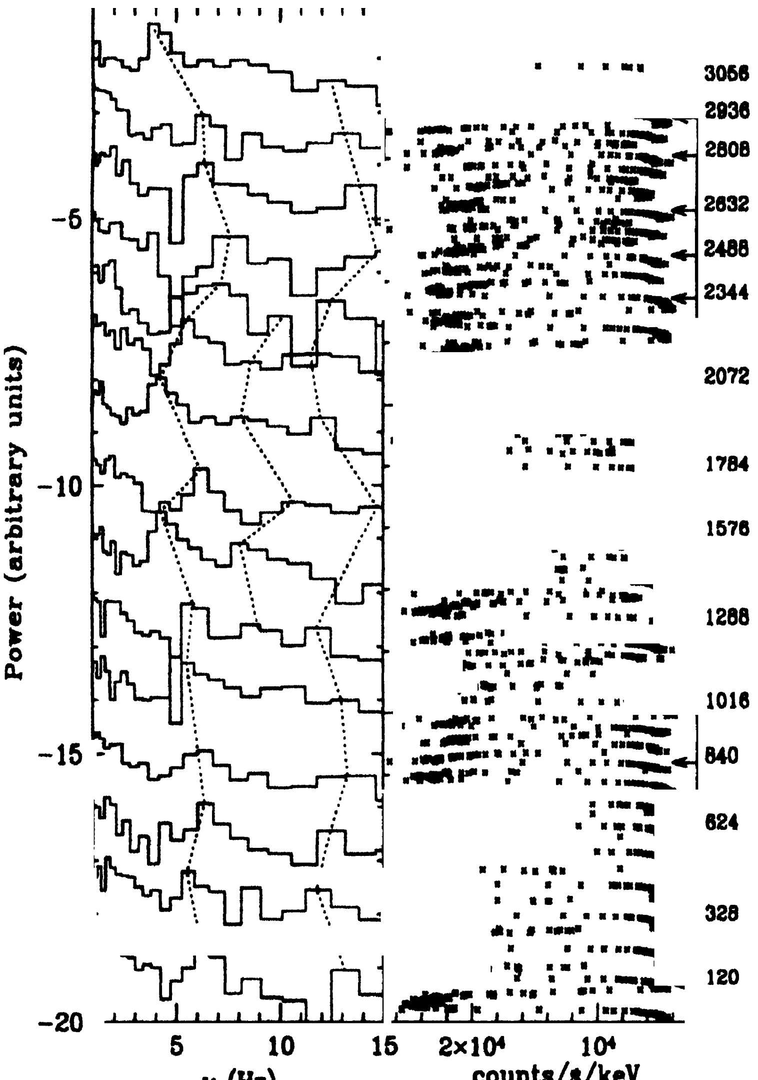

Figure 4. Plot of the light curve (right panel) and evolution of power density spectrum (left panel) of Case C data of June 18th, 1997. Off-states analyzed are marked by the time of observations on the right axis. The QPO frequencies are connected by a dashed curve to highlight the evolution of ν_{QPO} with time.

2.3. *Results of Case C*

Figure 4 is drawn using data of Case C (June 18th, 1997). The right panel shows the high degree of irregularity in the duration of the off states. Similarly, apparent chaotic variation of the QPO frequency is also seen in the left panel. There are weaker peaks in the spectra which are also connected by

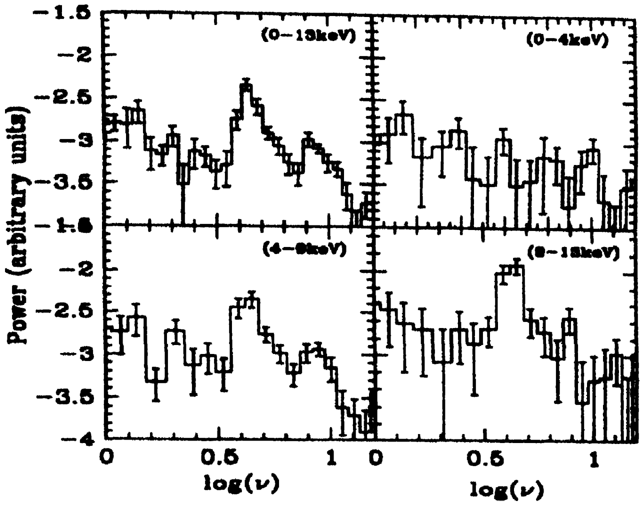

Figure 5. Power density spectrum of the off-state centered at 1576s. QPO is seen only in high energies, strongly pointing to the shock oscillation model.

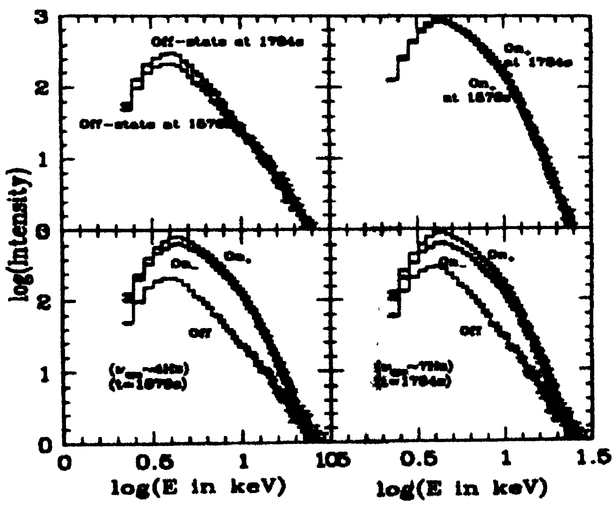

Figure 6. : Spectra of the off-states centered around 1576s and 1784s and two flanking on-states for each of them. See text for details.

dashed curves to highlight that these are also varying in the same way as the strongest peak (leftmost dashed curve). The two dashed curves on the right may therefore be just the harmonics.

Figure 5 shows the power density spectrum of the off-state centered around 1576s. The upper-left box shows the power spectrum for the full range of energy channels (0-13keV). A prominent QPO is seen at $\sim$ 4.5Hz and a possible harmonics at around 9Hz is also present. In the soft X-Ray region (0 – 4keV) there is no QPO (upper-right). In the (4 – 9keV) region (lower-left) the QPO is seen and in 9 – 13keV (lower-right), it is also strongest. This agrees with shock-oscillation model of QPO [5, 11].

Figure 6 shows spectra of two off-states centered around 1576s and 1784s and two flanking on-states for each of them. The on-state prior to the off-state is denoted as On_- and the on-state just after the off-state is denoted as On_+. There are several points to note here. In the upper-left panel, off-state (at 1576s) with lower QPO frequency (Fig. 4) is harder and fainter than the off-state (at 1784s) with higher QPO frequency. Second, while On_+ states are basically equally luminous (upper-right box) there is a significant variation of luminosity between on and off-states (lower boxes) and definitely some variation between On_+ and On_- states. In fact, On_+ is more luminous than the On_- state. Another result of importance is the intersection point (pivot) of the hard and soft spectra. Chakrabarti [12] shows that this intersection should take place at higher energies when wind is present. This object showed intersection of low-hard and high-soft states spectra at around 15keV (see, [7]) while our result shows intersection at around 20keV indicating presence of winds.

3. Discussions of Results

Essential observational results based on our analysis are the followings:

1. QPO frequencies are highly variable in time scales of hundreds of seconds.
2. The duration of Off-states and On-states are also highly variable.
3. Spectrum of the Off-states is similar to the usual low-hard states.
4. Spectrum of the On-states is similar to the usual high-soft states.
5. QPOs disappear at low energies.
6. Strong QPOs are seen only in hard states. In soft states very weak QPO feature (at a completely different frequency) may be present.
7. The Intersection of the On-Off states take place at a higher energy.

We now briefly present the explanations of these results based on the Chakrabarti-Titarchuk [5] model of the accretion flow. The rigorous hydrodynamic solution is in Chakrabarti [13]. The basic features of these advective flow models are:

(a) Accretion matter contains both the Keplerian and the sub-Keplerian flows. High viscosity Keplerian matter is on the equatorial plane while sub-Keplerian matter surrounds it all around.

(b) When relative abundance of Keplerian matter is high compared to the sub-Keplerian matter, soft-state is formed. Hard state is formed exactly in the opposite situation.

(c) The sub-Keplerian matter may form stationary or non-stationary shocks. Shocks may oscillate in time scales of $t_{osc} \sim 4r_s^{-3/2}(2GM/c^3)$s where r_s is the shock location in units of Schwarzschild radius and G, M, and c are the gravitational constant, mass of the black hole and velocity of light respectively. The factor of 4 arises due to strong shock assumption [11].

(d) Outflows may form in the centrifugal pressure dominated boundary layer [8, 14] depending on the compression ratio of the accreting gas. This is also verified by numerical simulations [15]. Presence of outflows shifts pivoting point [12].

(e) Typical volume to be filled by matter in between two off-states is proportional to r_c^3, where r_c is the sonic point, which is typically proportional to r_s, the location of the shock radius [8].

(f) The duration of the off states is determined by the time it takes for the sonic sphere to be filled and the optical depth (due to Compton scattering) reaches larger than unity [8].

Features (e-f) above explains Results (1-2) above since location of the shock essentially determines the volume of the cavity to be filled by the outflowing matter. Thus the oscillating shock frequency and the duration are related. Indeed we see that off-states with higher duration produce QPO with lower frequencies and vice-versa. See, Chakrabarti [9] for more details.

Features (b-c) above shows that solution with shocks would lead to hard-states while feature (f) shows that the accumulated matter in the sonic sphere is catastrophically cooled down to produce soft-states. Cooled down matter will have no shock and therefore no QPO. This explains Result (6) above. Combination of these points also lead to Results (3-4) above.

Feature (a) above leads to the fact that photons from Keplerian disk is intercepted by the oscillating post-shock flow. Since the pre-shock flow is only weakly affected by this oscillation, soft photons should not participate in the oscillation. This explains Result (5) above.

Feature (d) explains Result (7) above.

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